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Award Number: DAMD17-02-1-0593

TITLE: X-Ray Polarization Imaging

PRINCIPAL INVESTIGATOR: Andrew D. Maidment, Ph.D.

CONTRACTING ORGANIZATION: Thomas Jefferson University
Philadelphia, PA 19107

REPORT DATE: July 2003

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
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20040226 095

REPORT DOCUMENTATION PAGEForm Approved
OMB No. 074-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY
(Leave blank)**2. REPORT DATE**
July 2003**3. REPORT TYPE AND DATES COVERED**

Annual Summary (24 Jun 2002 - 23 Jun 2003)

4. TITLE AND SUBTITLE

X-Ray Polarization Imaging

5. FUNDING NUMBERS

DAMD17-02-1-0593

6. AUTHOR(S)

Andrew D. Maidment, Ph.D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)Thomas Jefferson University
Philadelphia, PA 19107

E-Mail: maidment@rad.upenn.edu

**8. PERFORMING ORGANIZATION
REPORT NUMBER****9. SPONSORING / MONITORING**

AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012**10. SPONSORING / MONITORING
AGENCY REPORT NUMBER****11. SUPPLEMENTARY NOTES****12a. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE**13. ABSTRACT (Maximum 200 Words)**

Conventional mammography only evaluates the spatial arrangement of tissue in the breast, as it depends upon the fact that some materials absorb x-rays more than other materials (the x-ray energy must be deposited in the body to produce an image). We propose to investigate the potential of x-ray polarization imaging, by building an x-ray polarimeter (a device designed to measure polarization) and determine the factors that affect polarimeter design. Polarization radiography has the potential to supplement mammographic images with information about the function, composition, and metabolism of the breast. We plan to perform fundamental experiments regarding x-ray polarization to determine whether the effect is sufficiently large to allow it to be used to produce images. We also wish to measure the ability of key biological materials, including breast tissue, to alter the polarization of x-rays, and determine the accuracy with which we can measure this effect. This research is quite clearly, speculative, but the program described in the grant would give the experimental data necessary to clearly understand the benefits and limitations of attempting to image tissue using polarized x-rays. This annual report presents our research to date.

14. SUBJECT TERMS

Breast Cancer, Mammography, X-ray Polarization

15. NUMBER OF PAGES

14

16. PRICE CODE**17. SECURITY CLASSIFICATION
OF REPORT**

Unclassified

**18. SECURITY CLASSIFICATION
OF THIS PAGE**

Unclassified

**19. SECURITY CLASSIFICATION
OF ABSTRACT**

Unclassified

20. LIMITATION OF ABSTRACT

Unlimited

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1. Introduction

X-rays are transverse waves; thus, one can preferentially produce x-rays in one polarization state. Passing through biological tissue, this state of polarization may be changed. Since x-rays are capable of passing through many inches of tissue, changes in the polarization state can reflect information about the tissue deep inside the body.

Conventional mammography only evaluates the spatial arrangement of tissue in the breast, as it depends upon the fact that some materials absorb x-rays more than other materials (the x-ray energy must be deposited in the body to produce an image). This new approach has the potential to supplement mammographic images with information about the function, composition, and metabolism of the breast. The ability to rotate the polarization of x-rays is conferred by the passage of the x-rays through the body, not the attenuation of the x-rays in the breast. Thus, while speculative, it may be possible to significantly reduce the dose needed to image the breast if an efficient imaging system can be constructed.

In this grant, we proposed to investigate the potential of x-ray polarization imaging. We proposed to build an x-ray polarimeter (a device designed to measure polarization) and determine the factors that affect its design. We plan to perform fundamental experiments regarding x-ray polarization to determine whether the effect is sufficiently large to allow it to be used to produce images. We also wish to measure the ability of key biological materials, including breast tissue, to alter the polarization of x-rays, and determine the accuracy with which we can measure this effect.

This research, while quite fundamental in its nature, has the potential for a significant impact in breast cancer diagnosis. The use of effects related to the polarization of x-rays is a largely unexplored field. Thus imaging based on this mechanism would represent a new way of non-invasively studying the human body.

These considerations are, quite clearly, speculative, but the program described in the grant would give the experimental data necessary to clearly understand the benefits and limitations of attempting to image tissue using polarized x-rays. This annual report presents our research to date.

2. Body

2.1. Statement of Work

The work for this grant was divided into four tasks. They are outlined as follows:

TASK 1: DESIGN AND DEVELOP X-RAY POLARIMETER

The proposed x-ray polarimeter design is based upon an apparatus whereby the distribution of the scattered radiation is used to measure the polarization. The initial task in this project is to design and build this polarimeter. The following steps are necessary in this task

Mechanical Design: A mechanical design for the gantry will be made.

X-ray source: The exact operating conditions of the polarimeter will need to be calculated and appropriate x-ray equipment assembled.

Analyzer: The analyzer acts to scatter the polarized x-rays. Performance is dependent upon the composition, shape and size of the analyzer, which will be tested with a theoretical analysis and experimental verification.

Beam stop: A carefully designed beam stop is necessary. The efficacy of various beam stop designs will be investigated using EGS Monte Carlo code (or equivalent).

Shielding: A critical element to this experiment is the shielding. The shielding, collimator, and material holder will have to be carefully designed with a series of Pb baffles to avoid excessive scatter from objects other than the analyzer. If necessary, EGS Monte Carlo simulations will be applied to aid in the design of the shielding.

Detector and associated electronics: The choice of the detectors and detector electronics will be made based upon estimated photon fluence, necessary signal-to-noise ratio (SNR) to observe polarization, cost, and other factors.

Control computers and operating software: It shall be necessary to write software that can operate the x-ray generator, motion systems, and detector readout (MCA or electrometer) in a coordinated fashion.

Data Analysis Software: It shall be necessary to write software to analyze the data obtained from the polarimeter.

Verification of Operation: As the system is designed, built and assembled, it shall be necessary to validate the operation of each component and of the system as a whole. We expect this to be an iterative procedure, which will require some time.

TASK 2: VALIDATE THE POLARIMETER DESIGN

Detector Calibration: Since four detectors are to be used in the experiment, and yet the data is to be combined, we will need to calibrate the detectors.

Data Fitting: It is necessary to fit the data obtained in these experiments to determine the polarization angle. Algorithm to perform this operation must be designed.

Linearity of Polarization Measurements: We propose to measure polarization as a function of thickness for some key materials.

Effect of kVp, target material and filtration: To determine the operating conditions for the polarimeter, we will measure P_{pol} for a variety of combinations of kVp, filter material and filter thickness. The energy spectrum of the scattered beam will be measured for each combination.

Effect of kVp and atomic number: The effect of kVp on the optical activity measured for certain key materials (e.g., as suggested above), will be tested. In addition, the effect of binding energy on polarization will be tested by measuring the polarization obtained with high-Z materials above and below the K-edge.

TASK 3: TABULATE OPTICAL ACTIVITY FOR COMMON MATERIALS

We will catalog the optical activity of various biological and inorganic materials.

TASK 4: POSTULATE THE DESIGN OF AN IMAGING SYSTEM(S)

Using the information gathered above, we shall postulate upon the likelihood of success of polarization imagers, and evaluate a variety of possible designs.

2.2. Administrative Note

The work in this grant commenced July 27, 2003. However, effective February 1st, 2003, Dr. Maidment resigned his position at Thomas Jefferson University and began working at the University of Pennsylvania. The majority of the work reported was performed while at Thomas Jefferson University, although work has continued at the University of Pennsylvania unfunded. It is Dr. Maidment's desire and intent to continue this research project at the University of Pennsylvania. Dr. Maidment is in the process of transferring this grant to the University of Pennsylvania. Thomas Jefferson University has already relinquished the grant and returned the unspent funds to the DOD. A one-year no-cost extension will be requested concurrent with the transfer request.

2.3. Background:

2.3.1. Polarization and Optical Activity:

Most biological materials are optically active to visible light. Like other materials, optically active materials can refract, absorb and scatter light, but in addition they respond differently to radiation, depending upon whether it is left or right circularly polarized. The differential absorption of light of these two polarizations is called circular dichroism, and the differential refraction is called circular birefringence, which for plane-polarized light is observed as optical rotation. Plane polarized light is composed of equal amplitudes of left- and right-polarized light. The magnitude of the optical rotation of plane-polarized light is proportional to the difference between the indices of refraction for left and right circularly polarized light and the thickness of the optically active material.

2.3.2. X-ray Polarization

Like other forms of electromagnetic radiation, x-ray photons can exhibit phenomena related to polarization. Bremsstrahlung x-rays produced by electrons accelerated from the cathode to the anode of an x-ray tube are partially plane-polarized with the electric field vector parallel to the cathode-anode axis [Dyson90, Agar79]. Classically, an accelerating

or decelerating charged particle emits radiation whose electric field vector (at each point in space) is coplanar with the axis of acceleration or deceleration [Barut80, Rohr65, Schwing98, Jackson99]. The physical reason for this geometric fact is clearer in the related process of an electron being scattered by a photon, as it is the electric field of the incident (or emitted) photon which is chiefly responsible for accelerating (or decelerating) the electron. By way of comparison, synchrotrons produce coherent, circularly polarized radiation.

The Bremsstrahlung radiation of diagnostic x-rays is on the order of 5-10% polarized, with greater polarization for x-rays whose energy is nearly that of the incident electron. Lower energy x-rays are produced by processes in which the electron's direction might have changed prior to emission of the x-ray, and thus have less polarization. These effects were experimentally documented as early as 1905 [Barkla05], as reviewed in [Steve57]. More recent research has tended to deal with thin targets (for example, [Kuck73]) so that the kinematics at the interaction vertex are well defined. A measurement of polarization from a Phillips x-ray tube [Staun78], in a study aimed at crystallographic applications, showed general agreement with the older results. Similar agreement was reported in an abstract [Slivin71].

2.4. Experimental Results

2.4.1. Poly-energetic x-ray Polarimeter Design

Although there are many ways to measure the polarization of mono-energetic x-ray beams, there is one prime method of measuring polarization of *poly-energetic x-ray beams*. This polarimeter design relies upon the angular distribution of the scattered beam to measure the polarization of the incident beam. Such a polarimeter is shown in Figure 1. It consists of a collimated x-ray tube, an analyzer, and two x-ray detectors at right angles. To measure polarization rotation by a sample material, the material must be placed in the primary beam, and the detectors must be mounted on a rotating gantry. In such experiments, the intensity of the scattered radiation recorded by the detectors would have a sinusoidal angular dependence.

The angular dependence of x-rays scattered from a polarized beam can be understood at the classical level. If a plane-polarized wave is incident upon a charged particle, the resulting acceleration \mathbf{a} of the particle will be parallel to the electric vector \mathbf{E}_{in} of the incident wave. The electric field component of the resulting scattered radiation at a distance R away from the scatterer in the direction $\hat{\mathbf{n}}$ (a unit vector) will be proportional to $\hat{\mathbf{n}} \times (\hat{\mathbf{n}} \times \mathbf{a}) / R$ [Barut80, Rohr65, Schwing98, Jackson99]. This formula has a simple geometric interpretation in that the electric field vector is proportional to the acceleration projected onto a plane perpendicular to the line of sight from the field point back to the scatterer. For a wave moving along the z-axis and plane polarized so that the electric vector lies along the x-axis (parallel to the anode-cathode axis), the angular distribution of scattered radiation per solid angle will have the form

$$d\Phi/d\Omega = r_e^2 [1 - \sin^2(\theta) \cos^2(\phi)]$$

where θ is the polar angle ($0 < \theta < \pi$) and ϕ is the azimuthal angle ($0 < \phi < 2\pi$).

The azimuthal variation is maximal for scattering at 90° relative to the incident radiation ($\theta=\pi/2$). In this plane, scattering would be 100% suppressed at $\phi=0$ or π (the direction of the electric field vector \mathbf{E}_{in} of the incident beam) if the beam were completely polarized.

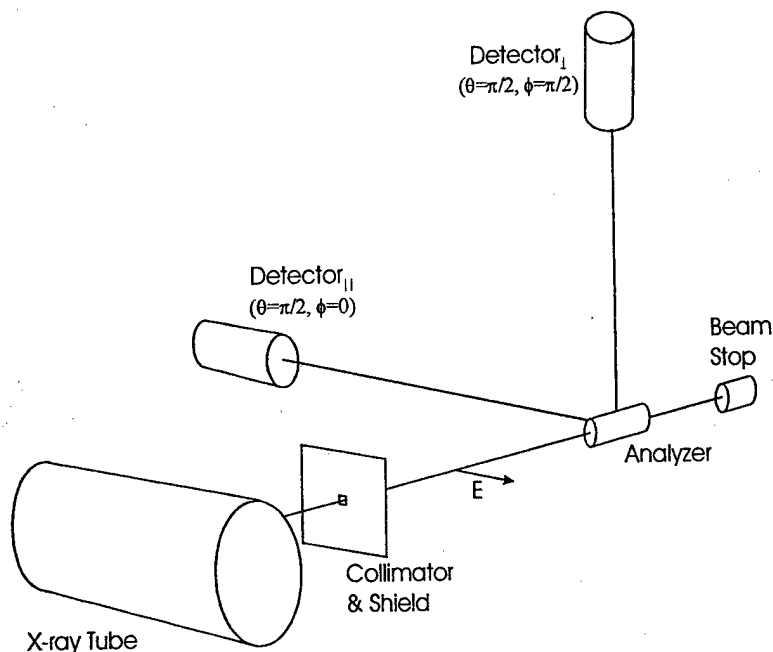


Figure 1: Schematic of the Polarimeter

For incompletely polarized beams, the azimuthal variation will be less pronounced. Using radiation scattered at 90° , if I_{\parallel} represents the intensity of the scattered radiation in the direction parallel to the preferred direction of the electric field vector ($\phi=0$) and I_{\perp} represents scattering in the orthogonal direction ($\phi=\pi/2$), the degree of planar polarization of the incident beam can be quantified in terms of $P_{pol} = (I_{\perp} - I_{\parallel}) / (I_{\perp} + I_{\parallel})$ which would be 1 for a completely plane-polarized beam and is on the order of 0.05-0.1 for conditions similar to clinical x-ray tubes.

2.4.2. Poly-energetic Experiments:

Barkla [Barkla05] and others have demonstrated polarization of conventional x-ray tubes. However, such experiments have been chiefly concerned with the nature of the Bremsstrahlung process or, for the earliest experiments, the nature of x-rays themselves. Work on optical activity in the x-ray region has generally used low energy x-rays ($<1\text{keV}$). The only known measurement of optical activity at diagnostic energies is for quartz ($3.5^\circ \pm 1.3^\circ$ at 19 keV) [Hart81].

We have conducted experiments using an apparatus similar to that shown in Figure 1. The analyzer consisted of a Lucite rod 2.5 cm diameter, and 13 cm long. The analyzer was positioned 40 cm from a tungsten target x-ray tube (Siemens Bi 150/30/50R), operated at 100 kVp and 100 mAs. The x-ray beam was collimated by a 6 mm diameter circular aperture, located 20 cm from the x-ray source. Thus, the irradiating beam was 12 mm in diameter at the analyzer. Two ion chambers were mounted at right angles to the beam, and at right angles to each other ($\theta=\pi/2$, $\phi=0$ and $\pi/2$), 60 cm from the analyzer.

The primary photon fluence incident upon the analyzer was estimated to be 2×10^{11} , while the scattered fluence at the detector in the direction perpendicular to polarization was $2 \times 10^6 \text{ cm}^{-2}$. We have thus observed x-ray polarization, measuring $P_{\text{pol}}=0.10$.

2.4.3. Pseudo Mono-energetic Polarimeter Design

Due to advances in our work with molybdenum $K\alpha$ radiation sources, we have begun to examine a possible polarimeter design based on a molybdenum x-ray source and a calcite crystal placed at 45° to the x-ray beam. The calcite will reflect the $K\alpha$ radiation at a Bragg angle of 45° (reflected beam is emitted at 90°) on the 11 0 1 plane of the crystal, so that the reflected beam is 100% polarized. The complete polarimeter is shown in Figure 2. The polarimeter consists of an x-ray tube, a reflecting crystal, a series of collimators to isolate the x-ray energy desired and to eliminate scattered radiation, a sample holder, and a detector consisting of an x-ray image intensifier and CCD camera. A sample image of the reflected x-ray beam is shown in Figure 3, with a sample polarization scatter image is shown in Figure 4.

This has the advantage rather than attempting to measure changes in polarization with a signal of 10%, the signal has 100% amplitude. There are two problems with this technique. First, only a small fraction of the incident x-rays are so reflected, thus the signal recorded is very weak. Secondly, the x-rays scattered by the sample need to be scattered at close to 90° to show 100% polarization. This further reduces the number of scatter events that can be successfully recorded. In the image shown in figure 4, the scatter angle is about 10° . Thus, we were unable to convincingly demonstrate polarization effects. Before conducting these experiments, it was not clear which method would be more sensitive to changes in polarization angle. We continue to analyze these results. We will make a determination of the best instrument design in the next two months, and will commence construction and component optimization at that time.

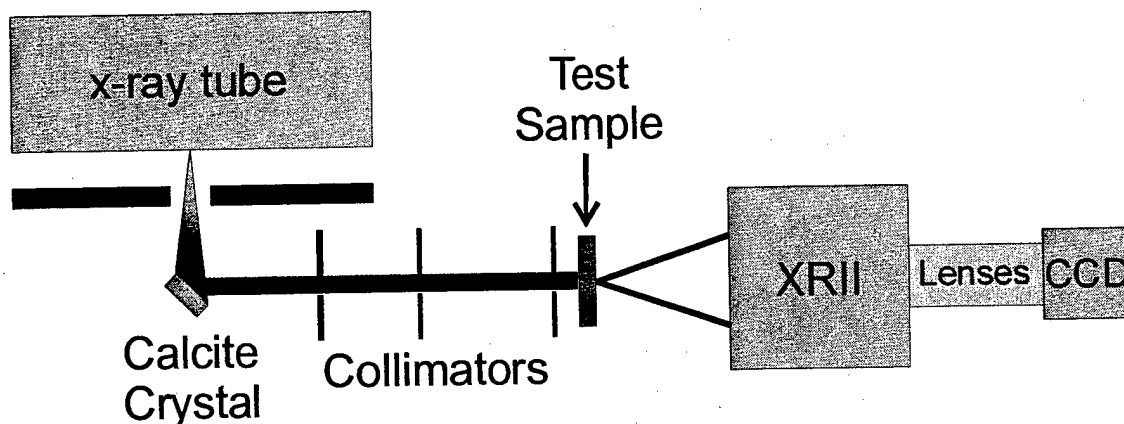


Figure 2: The schematic for the mono-energetic polarimeter. The x-ray tube produces a poly-energetic spectrum. The calcite crystal reflect the $K\alpha$ radiation ($\sim 17.3 \text{ keV}$) at 90 degrees. This polarized, mono-energetic beam is passed through a series of collimators and hits the test sample. The test sample then scatters the incident x-rays. The angular distribution of the scattered x-rays varies due to the x-ray polarization. This image is produced with the x-ray image intensifier (XRII) and then recorded by the CCD.

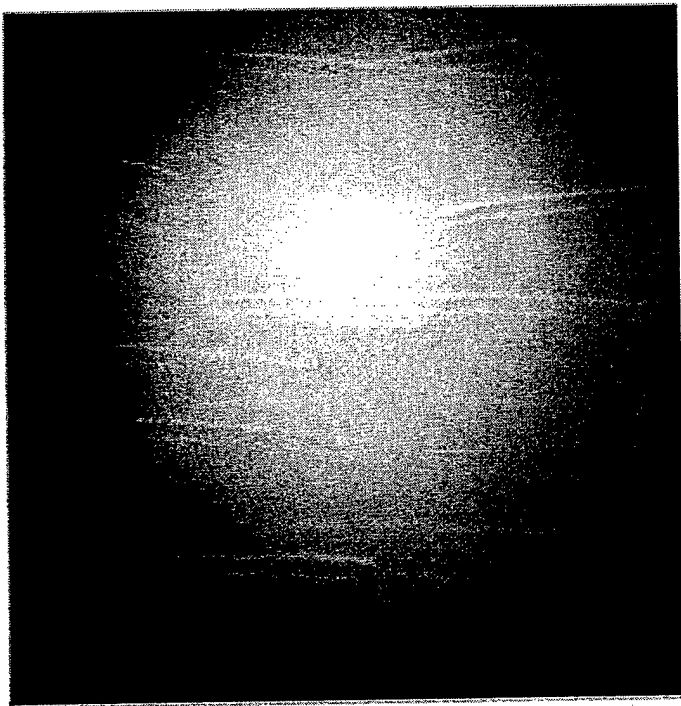


Figure 4: An image of the reflected x-ray beam without intervening collimation. The $K\alpha$ lines are clearly seen. Multiple lines are seen due to imperfections in the crystal. A cross-section through this image and a similar image filtered with niobium is shown in Figure 6.

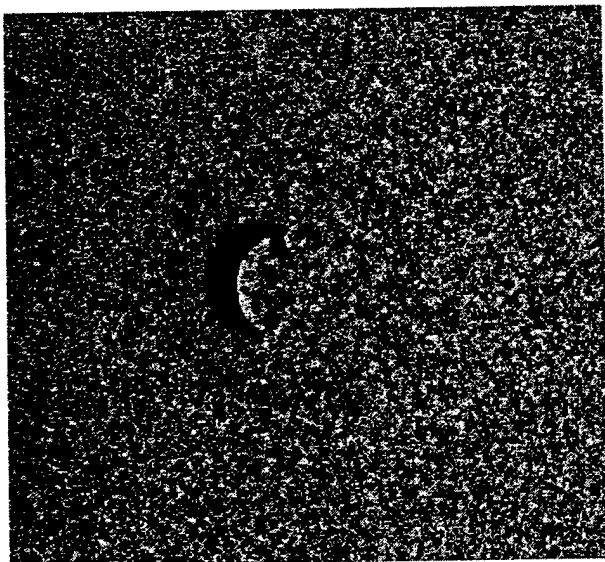


Figure 5: A single $k\alpha$ line was selected to interrogate a thin layer of wax. Shown is the beam scattered at an angle of approximately 10 degrees. (The crescent shape is an artifact). The beam appears to scatter more in the vertical direction as expected. The image, however, is quite noisy due to limitations on x-ray exposure.

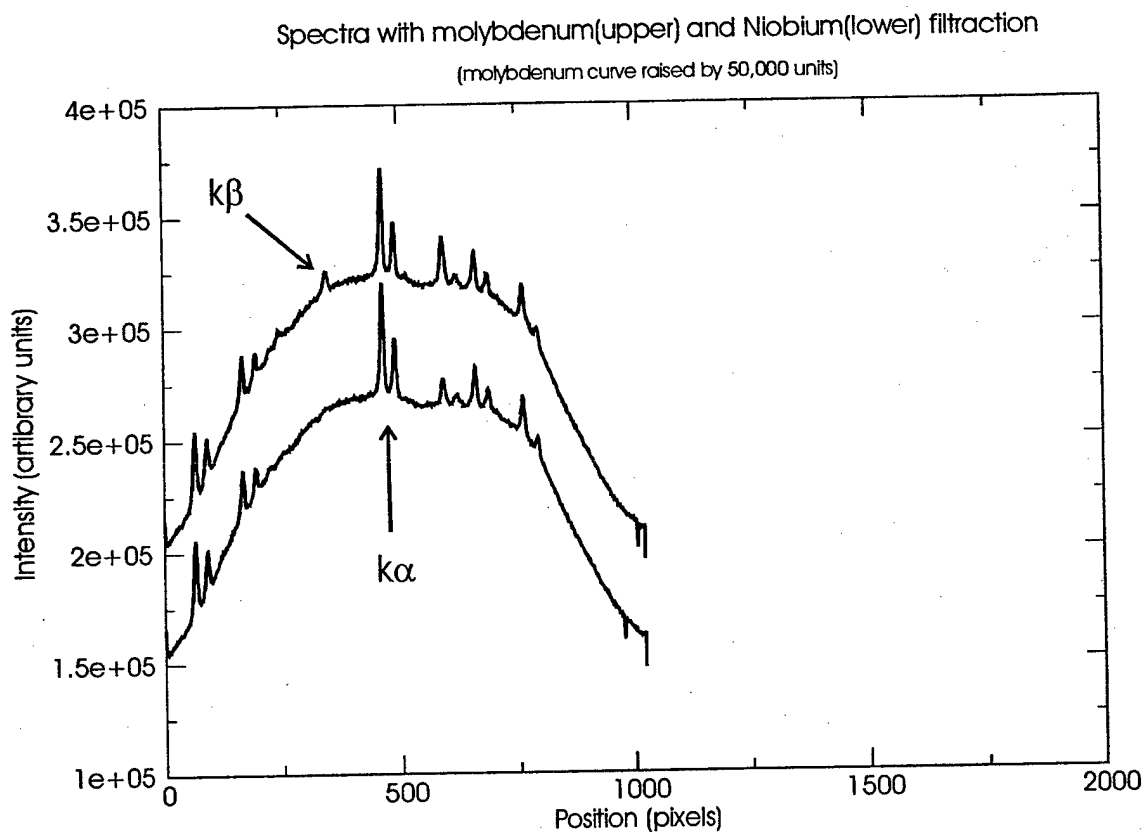


Figure 6: The intensity of as a function of position across the x-ray detector. The two graphs differ by the beam filtration. One allows $k\beta$ radiation to be imaged, the other does not. Note that the $k\beta$ lines are missing in the one graph. The two graphs are displaced for illustrative purposes only. Due to imperfections in the crystal used, there are multiple replicates of the K lines.

3. Key Research Accomplishments:

Since the start of the grant, we have tested two different methods of producing and evaluating polarized x-rays. We are currently comparing the relative strengths of each method. We will soon be in a position to construct the polarimeter to be used for the remaining experiments in the grant. The work has been interrupted due to our move from Thomas Jefferson University to the University of Pennsylvania. We are currently awaiting approval of the grant transfer and plan to continue this grant as soon as possible.

4. Reportable Outcomes:

None to date.

5. Conclusions:

At the conclusion of the first year of experiments, we have successfully been able to produce polarized x-ray beams and have begun to characterize the detectors used. We will soon begin permanent construction of the selected design.

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7. Appendices:

None.